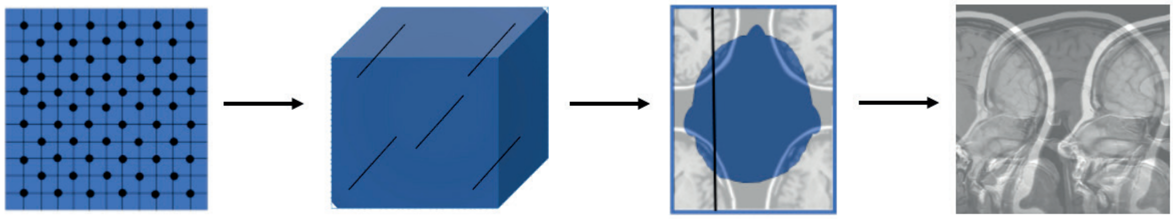

Fig.3 - *2D-CAIPIRINHA sampling method with slice-shift phase along phase Kz encoding and representation in terms of Aliasing.*

from the association, to the 2D-CAIPIRINHA method, of the Bunch Phase Encoding (BPE), that is a “Zig Zag” sampling along Gy and Gz, which determines a controlled aliasing on all three spatial directions. In association with the “slice-shift” effect of the 2D-CAIPIRINHA method, two sinusoidal gradients Gy and Gz are applied during the Gx gradient readout, with a shift of $\pi/2$, and this leads to the generation of a wave trajectory, defined more simply “corkscrew trajectory”, along the voxels (Figure 4). By combining these two additional sinusoidal gradients with the “slice-shift”, a well-distributed aliasing pattern is created on all three spatial dimensions. This allows Wave-CAIPI to fully exploit the information on the sensitivity of the coil, allowing a high R acceleration factor, with negligible noise amplification and reduced artifacts. In the domain of the image the additional phase deposition results in a diffusion along the only readout direction that varies linearly depending on the position along Gy and Gz. To better understand this concept, let’s analyze (as shown in Figure 6) what happens with the Gy application alone, not taking into account the gradient Gz applied and the slice-shift 2D-CAIPI. We can consider this Gy as an extra-phase modulation of K-space. In the image domain this results in the introduction of a PSF along the direction of the readout gradient, which also depends on the position along *y*. Thus, at the center of the FOV we will have a very little spread, namely a small PSF, while in the more peripheral areas of the FOV along the y-axis, we have an increasing diffusion. Considering the image domain, to understand what happens to a particular voxel, for each voxel there is a corresponding PSF that spreads with convolution of z. Wave-CAIPI, unlike other very fast acquisitions such as EPI, Radial imaging or Spiral, is not subject to blurring from data gridding or artifacts from distortion from uneven magnetic field B0, thanks to a constant crossing of k-space along the readout direction Kx, resulting in the same chemical displacement effect observed in conventional Cartesian imaging sequences. The Wave-CAIPI acquisitions, as previously mentioned, therefore can be reconstructed efficiently thus avoiding K-space data gridding processes. This is possible because the wave trajectory can be represented as additional phase deposition in Cartesian k-space. Using a PSF the voxel diffusion effect from Wave-CAIPI is modeled through a convolution that varies spatially in the image domain efficiently as a phase modulation in hybrid space (Kx, y, z).

Reconstruction and correction of the image in the Wave-CAIPI technique.

Characterizing with precision the effective trajectory of waves in order to correctly reconstruct and correct the image is crucial. Wave trajectories along phase coding Gy and Gz are estimated through fast scans in the x-y plane to characterize the Py-Wave, in the x-z plane to characterize the Pz-Wave through a double acquisition with and without the Wave gradient. The encodings created by the sinusoidal gradients Gy and Gz are convoluted through a PSF, and the k-space data and the PSF are put in relation. Thanks to the Fourier Inverse Transform, we get information about the additional phase effect imparted along the image domain, along the Gz and Gy phase encoding in the shift along the trajectory of the K-space.

$$Wave\,[x, y, z] = \sum_k e^{i2\pi kx/N}\,(e^{-i2\pi\,(Py\,[k]y\,+\,Pz\,[k]z)}) \sum m\,[x, y, z]\; e^{i2\pi kx/N}$$

or

$$Wave\,[x, y, z] = F_x^{-1} \cdot Psf\,[x, y, z] \cdot (F_x \cdot m\,[x, y, z])$$

This expression relates the acquired image with wave gradients (x, y, z), to the magnetization Mx, My, Mz,

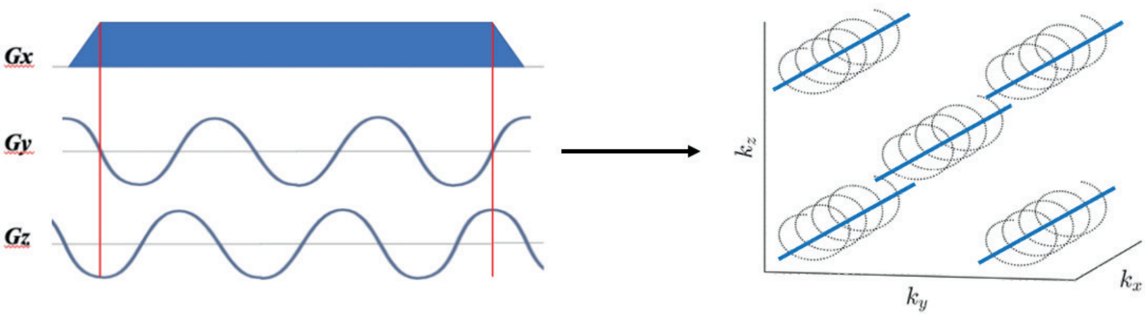

Fig.4 - *Wave-CAIPI sampling system. The sinusoidal gradients Gy and Gz with a offset of $\pi/2$ between waveforms run into a corkscrew trajectory in the k-space.. The waves are also offset thanks to the 2D-CAIPI sampling strategy to create the slice shift.*

and suggests a simple explanation for the effect of wave gradients: each readout line is convoluted with the PSF which depends on the spatial position (y, z) to produce the image of the acquired wave. In particular, Fx represents the Discrete Fourier Transform (DFT) along the readout encoding axis and the PSF represents the effect of Wave gradients. Note that the gradients of the Gy and Gz wave do not cause the diffusion of the voxel in y and z directions but the only diffusion effect is along the readout encoding. This effect is explained by the fact that Gy and Gz wave gradients combined with shifts along the volume of partitions create a diffusion in all directions of space. With the Wave-CAIPIRINHA technique, therefore, the Aliasing is spread along the three directions of the space with optimal correction of the sensitivity profiles of the 3D coils, which allows to obtain images with high SNR, with optimal geometric factor values g and higher acceleration factor values R, compared to other parallel imaging methods.

Clinical applications of the Wave-CAIPI technique in MRI

From a review of the scientific literature, some study groups applied the Wave-CAIPI method to the MP-RAGE sequence showing promising results, compared to conventional PI techniques, in terms of signal/noise ratio, acceleration of acquisition times, application of increasing acceleration factors and geometric factor. Longo et al have studied the application of the Wave-CAIPI MP-RAGE, compared to the MP-RAGE with GRAPPA technique, demonstrating the same reliability and lower acquisition times with Wave-CAIPI while using higher R acceleration factors. A further study, conducted by Polak et al, compared the Wave-CAIPI technique with the 2D-CAIPI applied to the MP-RAGE, demonstrating a better SNR, with lower values of g factor, equal acceleration factor R, isotropic resolution and acquisition times. In addition, the same study group then compared the Wave-CAIPI with the GRAPPA method applied to the MP-RAGE sequence, demonstrating that at the same isotropic resolution (1 mm) it is possible to obtain images with similar SNR, while using higher R acceleration factors in the Wave-CAIPI technique. Further evaluations and studies have been carried out to compare the Wave-CAIPI to other conventional parallel imaging techniques, such as GRAPPA and 2D-CAIPI, also in other fundamental 3D sequences in the field of Neuro-MR Imaging, such as T1 SPACE, SWI, SPACE FLAIR.

CONCLUSION

We have analyzed in detail the rapid acquisition technique Wave-CAIPI that allows to obtain images with high space and time resolution. The Wave-CAIPI technique, involving a subsampling of the k-space with 2D-CAIPIRINHA methodology combined with the trajectory of the Wave gradients, allows an optimal use of the intrinsic spatial information of the coils and allows a higher acquisition speed with reduced noise amplification and less artifacts. The Wave-CAIPI technique continues to evolve and expand into multiple volumetric sequences, constituting one of the most stimulating advances in the field of MRI.

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